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# Olfactory appraisal of odorants for 100% hydrogen networks

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## Abstract

To meet carbon emissions reduction targets heat and transport need to be decarbonised. Hydrogen is being considered as a flexible energy vector that could play an important part in this endeavour. With demonstration projects on the rise it is crucial to identify suitable odorants to ensure, safety regulations are met and public acceptance gained. Specifically, this work investigates the use of sulphur based odorants currently in use in the UK and Europe, alongside sulphur-free and experimental ones, for use in a 100% hydrogen gas demonstration network in the UK. Gas samples odorised with five different odorants are analysed to determine odour detection threshold, the odour intensity, its hedonic tone and character. The tests are performed by an accredited laboratory following EU standards. The results show that four odorants meet requirements as stenching agents for use in UK gas distribution network, whilst one, 5-ethylidene-2-norbornene, fails to demonstrate an unpleasant odour.

## Introduction

Decarbonisation of our energy systems worldwide is necessary to achieve the greenhouse gas emissions reduction targets set by recent national and international commitments (BEIS, 2017; UN, 2015). In the UK for example over 60% of carbon emissions are due to heat required for industrial processes, domestic heating, and transportation (BEIS, 2017). These carbon emissions could be significantly reduced by using hydrogen (Dodds & Demoullin, 2013; Godula-Jopek & Westenberger, 2015; Wulf & Kaltschmitt, 2016). In addition hydrogen is inexhaustible and not

27 dependent on foreign control to ensure security of supply (Najjar, 2013). It is also versatile, energy-efficient, and a  
28 high-quality energy carrier (Najjar, 2013). In countries relying on natural gas for domestic heating, such as the UK  
29 which has 84% of households connected to the natural gas network, hydrogen could allow end users to keep using  
30 combustion boilers and cookers as they do today, and offer a decarbonised and enduring future for gas  
31 infrastructure developed and upgraded over the past half-century (Dodds & Demoullin, 2013).

32 Hydrogen can be produced from natural gas using steam methane reformation, which, when combined with carbon  
33 capture and storage is almost carbon neutral, or from the electrolysis of water using potentially variable renewable  
34 energy sources (Ball & Weeda, 2015). The end user can either use the hydrogen in fuel cells or combust it in boilers  
35 and other appliances. This highlights the flexibility hydrogen has to offer from both a generation and end-use  
36 perspective (Barreto, Makihiro, & Riahi, 2003).

37 One of the requirements that hydrogen would have to meet in order to be widely used in gas distribution networks  
38 providing gas to homes and cities is to be odourised (Dodds & Demoullin, 2013; Puri, 2006). Odourants have been used  
39 in natural gas for over a century providing an early warning system enabling leaks to be identified and managed and  
40 made safe before flammable levels are reached (Kilgallon, Gilfillan, Haszeldine, & McDermott, 2015). Proposals to  
41 odourise gas was first suggest by R. Von Quaglio in Germany, during the 1880's, yet it was only in 1918 that Germany  
42 began odourising gas on a small scale, followed by the United States of America (Amirbekyan, 2013; Kilgallon, Gilfillan,  
43 Haszeldine, & McDermott, 2015). In 1937, a natural gas explosion occurred in the New London School in Texas killing  
44 298 people (May, 2010). Non-odourised gas had been leaking in the building following a change of provider. Following  
45 the incident the 45<sup>th</sup> Texas Legislature made the addition of mercaptan odourant to gas supplies mandatory (Kilgallon,  
46 Gilfillan, Haszeldine, & McDermott, 2015). This safety procedure then became common worldwide, and is used to  
47 this day as a standard procedure in gas transportation via pipelines (Kilgallon, Gilfillan, Haszeldine, & McDermott,  
48 2015). In 1978, odourisation of hydrogen gas for domestic use in appliances has even been proposed to control the  
49 safety problems to at least the acceptable levels for gas fired appliances at the time (Brewer, 1978).

50 In the UK and Europe, odourants should make any leaked gas detectable before it reaches 20% of its lower  
51 flammability limit (that is the minimum gas volume concentration in air required for the gas mixture to ignite) (Fink,  
52 2015) (BS EN ISO 13734:2013). For hydrogen, the lower flammability limit is 4%v and hence hydrogen leaks should  
53 illicit an olfactory response corresponding to a 'medium odour' before concentrations reach 0.8 %v, which is  
54 approximately equivalent to that of natural gas at 1.0%v (Kopasz, 2007). The olfactory response corresponding to a

55 'medium odour' is of 2 olfactory degrees on the Sales scale. Hydrogen is naturally odour free and as such odorant  
56 has to be added to it.

57 At the concentrations found during transport, odorants must be non-toxic to humans, animals and the environment  
58 (BS EN ISO 13734:2013). Moreover, it has to be stable and not degrade during transportation and storage of the  
59 hydrogen (BS EN ISO 13734:2013). Besides, it is essential that odorants suitable for the targeted end-uses be used.  
60 Current natural gas odorants are mostly sulphur based, such as mercaptans (BS EN ISO 13734:2013). Sulphur  
61 compounds are toxic for fuel cells, which is one end-use for hydrogen(de Wild, Nyqvist, de Bruijn, & Stobbe, 2006;  
62 Kopasz, 2007). However, odorants in use today have no impact on appliances combusting gas, like boilers, which are  
63 also likely to be a substantial end use for distributed gas in countries with a strong cultural link to them, such as the  
64 UK and Netherlands (Dodds et al., 2015). As of yet, there currently is no widely accepted odorant compatible with  
65 hydrogen fuel cells (Anstrom, 2014). This problem is being considered and ways of removing sulphur compounds  
66 from a gas stream are being investigated (Madi et al., 2016). Adsorptive desulfurization is one of the most  
67 investigated desulphurisation methods in fuel processing for fuel cells because of its high efficiency and of its  
68 simplicity (Ho, Lee, Lee, & Woo, 2014). A review on the impacts of contaminants, including sulphur organic  
69 compounds, on fuel cells can be found in Cheng et al. (2007). For future domestic fuel cell end uses it is important to  
70 find an efficient small scale solution to desulfurization of hydrogen gas, or a sulphur-free odorant.

71 Generally, odours comprise of a complex mixture of chemicals that are released into the air. Reaction of the  
72 olfactory nerve in response to odour, elicits the perception of smell. Odours can be detected and recognised at very  
73 low concentrations. The response by sensitive receptors is subjective as all people have a unique set of cells. Odours  
74 can be perceived as either neutral, pleasant, or unpleasant. This strictly depends on several factors such as; genetics,  
75 first-hand experience, and cultures. Odours can be transported over long distances through atmospheric circulation  
76 and thus impact the broader population.

77 The UK's Department for Business, Energy and Industrial Strategy commissioned a report which highlights the need  
78 to investigate the odorants currently in use in the natural gas network when mixed with 100% hydrogen. The work  
79 reported here, undertaken under the H100 project led by SGN, is directly referred to as the underpinning research  
80 needed to inform the use of odorant in a decarbonised 100% hydrogen gas network (Frazer-Nash Consultancy,  
81 2018).

82 This study investigates the olfactory profile of hydrogen odorised with five different odorants. Odorant currently in  
83 use in UK and EU gas networks are tested as well as commercial and experimental sulphur-free ones. The aims of the  
84 assessment was to determine the suitability of five odorants to be used as a stenching agent in a 100% hydrogen gas  
85 distribution network trial of up to 300 properties based on:

- 86 1) Suitable strength to allow detection?
- 87 2) Can be detected at suitable intensity?
- 88 3) Is the odour characteristically unpleasant?
- 89 4) Is the odour distinguishable from other common ones?

90 This work provides an assessment of the odour threshold concentration for each odorised gas sample, this is a  
91 measure of the relative strength of each odorised sample. This was followed by an odour intensity test to determine  
92 if the gas sample can be perceived as a medium odour intensity. Then a hedonic tone test to determine the  
93 pleasantness/unpleasantness of the sample is performed. Finally, an odour character analysis is done to determine  
94 the type of odour each odorant imparts and if the character is distinctive.

## Methods

### Odorant Selection

The five selected odorants are presented in Table 1. They include the Odorant ‘New Blend’ in use in the SGN UK networks, and its backup ‘Standby Odorant 2’ which is a dilution of Odorant ‘New Blend’ in hexane, common European network odorant THT, as well as a sulphur-free odorant used in Germany, GASODOR® S-FREE® (Cagnon, 2011; Kilgallon et al., 2015; Madi et al., 2016). We also investigate the potential of another sulphur free odorant that was identified as being compatible with fuel cells: 5-ethylidene-2-norbornene (Imamura, Akai, & Watanabe, 2005). The aim was to study proven odorants used in natural gas networks as well as odorants that would be compatible with fuel cells. All the odorants investigated were chosen as having potential to be used on a 100% hydrogen demonstration gas network due to be built in Scotland in 2020-21 by SGN. The end use of the hydrogen will be combustion in appliances only and as such sulphur compounds would be suitable for this particular demonstrator.

*Table 1: Rational behind odorant selection and concentration of odorants’ compounds in undiluted samples (i.e. as would be found in distribution networks). NB stands for ‘new blend’, TBM for ‘tert-butyl mercaptan’, DMS for ‘dimethyl sulphide’, THT for ‘tetrahydrothiophene’, MA for ‘methyl acrylate’, EA for ‘ethyl acrylate’, EMP for ‘2-Ethyl-3-methylpyrazine’.*

	Compound	Rationale	Concentration (mg/m3) in Gas Sample
1	Odorant NB (78% TBM), 22% DMS)	Primary odorant used by SGN and other UK gas networks (Kilgallon et al., 2015)	TBM: 5.57 DMS: 1.08
2	Diluted Odorant NB (standby 2) (34% Odorant NB, 64% Hexane)	Diluted form of Odorant NB used by SGN if supply of Odorant NB is compromised	Hexane: 4.51 TBM: 1.90 DMS: 0.37
3	Odorant THT (100% THT)	Most commonly used odorant within European gas networks (Cagnon, 2011)	THT: 17.99
4	GASODOR®S-FREE® (37.4% MA, 60.1% EA, 2.5% EMP)	Sulphur-free gas odorant in use within some German gas networks (Cagnon, 2011)	MA: 2.46 EA: 4.60 EMP: 0.23
5	5-ethylidene-2-norbornene	Odorant that is suitable for fuel cell applications (Imamura et al., 2005)	5-ethylidene-2-norbornene: 83.57

In all the investigations presented below a human panel carries out the testing. Six panellists are used, all are classified as “Trained assessors” having specific odour acuity in accordance with EN13725 dynamic dilution olfactometry. The work was undertaken at the ‘Odour Laboratory’ which is accredited (#8283) by the UK’s National Accreditation Body (UKAS).

## Odour threshold analysis

Triplicate samples were transferred from gas cylinders to an inert Nalophan sample bag for each odorant. Each sample was processed within two hours of its collection. The original gas samples tested had an odorant concentration equal to what would be expected in a 100% hydrogen gas distribution network.

The value measured is the detection threshold of the gas sample, not that of the reference material. Odour concentration is defined as the number of European odour units ( $\text{OU}_E$ ) per cubic meter of air ( $\text{OU}_E/\text{m}^3$ ). It is used as a way of expressing the relative strength of an odour. The European Odour unit is that amount of odorant that, when evaporated into 1 cubic meter of air or nitrogen at standard conditions (293 Kelvin, 101,300 Pascal) causes a physiological response in 50% of panel members which is equivalent to that caused by one European Reference Odour Mass (123  $\mu\text{g}$  *n*-butanol) evaporated into 1 cubic meter of air or nitrogen at standard conditions (BS EN 13725:2003). This physiological response corresponds to an olfactory degree 0.5 on the Sales scale equivalent to a perceived sensation of a 'very feeble odour'.

The reason for using this approach is that it allows for quantifiable replicable results to be obtained from a limited number of people. This is why *n*-butanol is chosen as a reference against which trained assessors can benchmark their physiological reaction to an odour stimulus (BS EN 13725:2003).

Samples were presented to panellists in an ascending order of strength (starting with the highest dilution first and the lowest dilution last). There are six dilution steps in each round of presentation. Each dilution step was presented to panellists for a twenty second period. There was a 10 minute pause between each sample test. Three rounds of sample presentation were carried out for each sample and the geometric mean calculated.

The dilution factor at which 50% of the panel experience a physiological response equivalent to a 'very feeble odour' is recorded (BS EN 13725:2003). This dilution factor represents the number of times the initial gas sample can be diluted and still be detected as a 'very feeble odour' (as per the  $\text{OU}_E$  definition above). Hence the odour threshold concentration of the gas sample, in  $\text{OU}_E/\text{m}^3$ , prior to dilution is equal to that dilution factor multiplied by the detection threshold (1  $\text{OU}_E/\text{m}^3$ ). Therefore, the higher the odour threshold concentration of the gas sample the more concentrated the sample odour is.

## Odour intensity

Following the average odour detection threshold concentration of the gas samples the odour intensity could be measured. Each gas odorant sample was presented at increasing concentrations starting at a concentration just

142 above its odour detection threshold to the panel. The Scentroid SS600 Olfactometer was used to present the diluted  
143 samples at a controlled flow rate through one sniff port. During the presentation of the sample at each  
144 concentration level, the panellists had to rate the perceived intensity using the Sales scale (Sales, 1958) in Table 2.  
145 The perceived intensity measurements from the panellists were done in three rounds for each odourised gas sample.

146



Intensity Scale (Olfactory degree)	Perceived Sensation
0	No odour
0.5	Very feeble odour (Odour detection threshold)
1	Feeble odour
2	Medium odour (alert level)
3	Strong odour
4	Very strong odour
5	Maximum odour

148

149 The Weber–Fechner law is fitted to the data (Fechner, 1860) (BS EN 13725:2003). This model uses two laws relating  
 150 to human perception. In particular, the relationship between the actual change in a physical stimulus (smell) and the  
 151 perceived change (odour intensity). This simple relationship is expressed by:

$$S = k \cdot \log I/I_0 \quad (1)$$

152 Where S is the perceived intensity of the odour, I is the odour concentration, I<sub>0</sub> is the threshold concentration, and k  
 153 is the Weber-Fechner coefficient or Weber ratio. Here k is taken as the slope of the linear relationship between the  
 154 normalised dilution levels (proxy for odour concentration) and the overall average intensity of the odour.

## 155 Hedonic tone

156 This test is performed once the odour detection threshold concentration of the samples had been determined.

157 Hedonic tone measurements are performed. Samples were presented to panellists at random dilution levels above  
 158 the odour detection threshold, two control blanks were included (fresh air). The samples were administered through  
 159 a single sniff port of a Scentroid SS600 Olfactometer. Three rounds of sample presentation were carried out for each  
 160 sample and the geometric mean calculated. Each dilution step was presented to panellists for a twenty second  
 161 period. There are six dilution steps in each round of presentation. There was a 10 minutes pause between each  
 162 sample test. The Hedonic tone scale used is presented in Table 3.

163 *Table 3: Hedonic tone scale to assess the pleasantness of the reaction elicited by the odorised gas.*

Hedonic tone classification	Perceived pleasantness / unpleasantness
+4	Very pleasant
+3	Pleasant
+2	Moderately pleasant
+1	Mildly pleasant
0	Neutral / no odour
-1	Mildly unpleasant
-2	Moderately unpleasant
-3	Unpleasant
-4	Very unpleasant

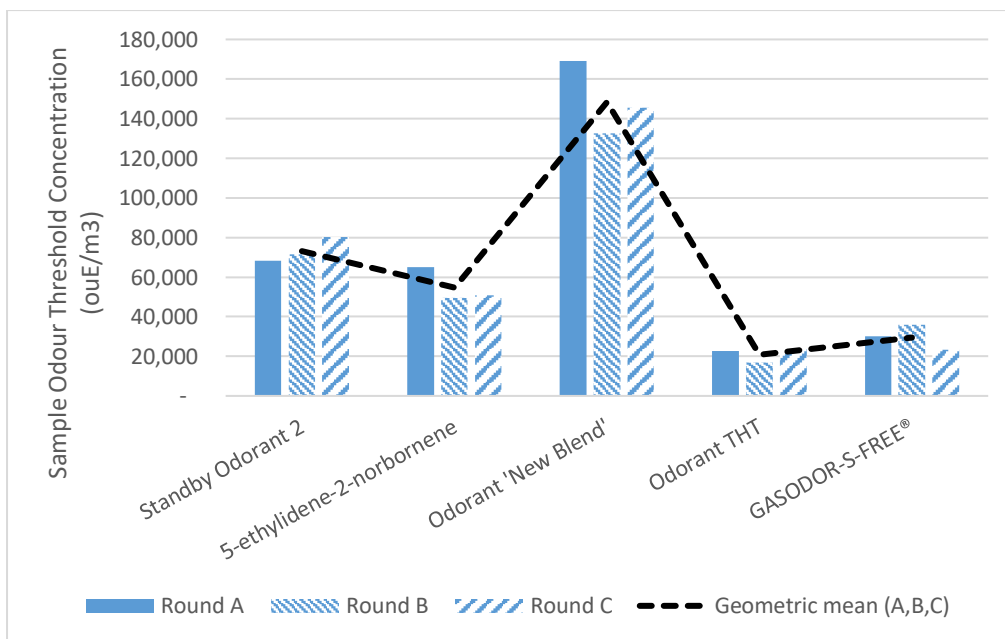
## 165 Odour character

166 The assessment of the character of each gas odorant was measured by presenting the odorised gas sample at a  
 167 controlled flow rate through one sniff port to the panel. They were asked to describe the type and nature of the  
 168 odour they perceived. Each sample was presented three times to each panellist for a period of 20 seconds. A 10  
 169 minute period elapsed between two sample tests. Direct presentation of the raw sample was conducted (with no  
 170 dilution) through a sniff port of a Scentroid SS600.

## 171 Results

### 172 Odour detection threshold analysis results

173 The odour detection threshold concentration of the gas samples are displayed in Figure 1. It can be seen that the gas  
 174 sample containing the Odorant 'New Blend' has the greatest odour concentration. It has an odour strength which is  
 175 more than double the second strongest odorant 'Standby Odorant 2'. The weakest odorant in terms of odour  
 176 detection threshold is 'Odorant THT'.



178 *Figure 1: Odour detection threshold analysis of the gas samples results. The Odorant 'New Blend' has the greatest sample odour threshold*  
 179 *concentration. The data was obtained from three individual rounds performed on triplicate gas samples obtained from a cylinder containing a*  
 180 *mix of odorant and hydrogen at concentrations expected in a gas distribution network.*

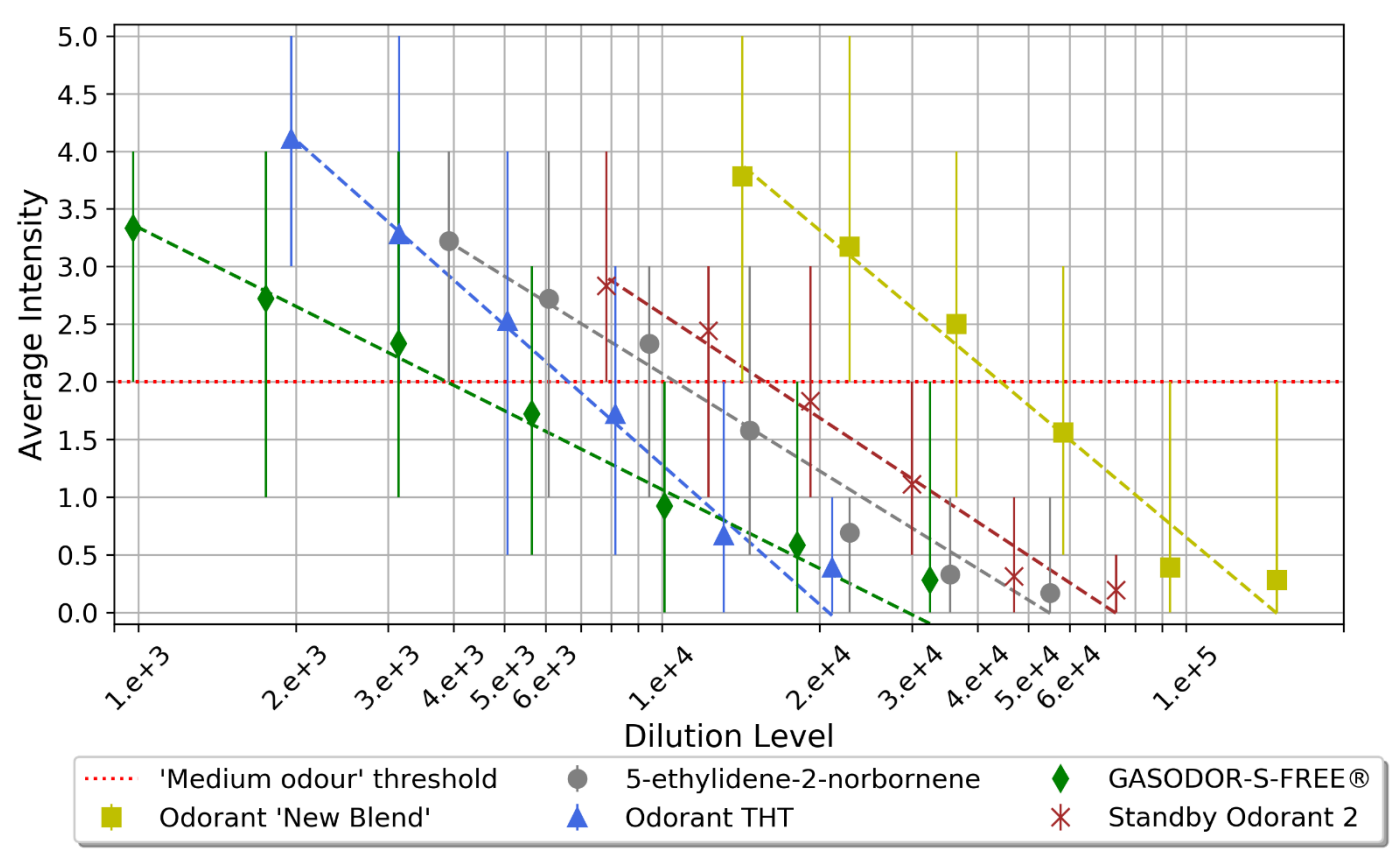
### 181 Odour intensity results

182 The result of the intensity perceived by the panellists at various dilution points of gas sample triplicates are reported  
 183 here. The aim is to identify the dilution point at which an odour intensity of 2 olfactory degrees on the Sales scale  
 184 (medium odour) is perceived by the panellists. The results show that all the gas samples offer intensity largely in  
 185 excess of 2° on the Sales scale when undiluted. The sample with the most potent odorant, 'Odorant New Blend' can

186 be diluted up to about 45,000 times before reaching the threshold of 2 olfactory degrees on the Sales scale. The  
 187 sample with the 'GASODOR®S-FREE®' odorant can still be diluted 4,000 times before reaching an intensity of 2° on  
 188 the Sales scale. The odorant with the steepest rate of intensity drop with dilution is 'Odorant THT'.

189 The dotted lines in Figure 2, also show that a good fit to the experimental data can be obtained using Weber-  
 190 Fechner's Law, which relates proportionally the perception to a stimulus to the natural logarithm of the stimulus  
 191 intensity. We note that goodness of fit decreases as the intensity drops below 1° on the Sales scale (i.e. as odour  
 192 concentration decreases). The fit to the data for intensities greater or equal to the threshold of 2° on the Sales scale  
 193 is good with a Pearson coefficient between all the data and the model in excess of 0.98.

194



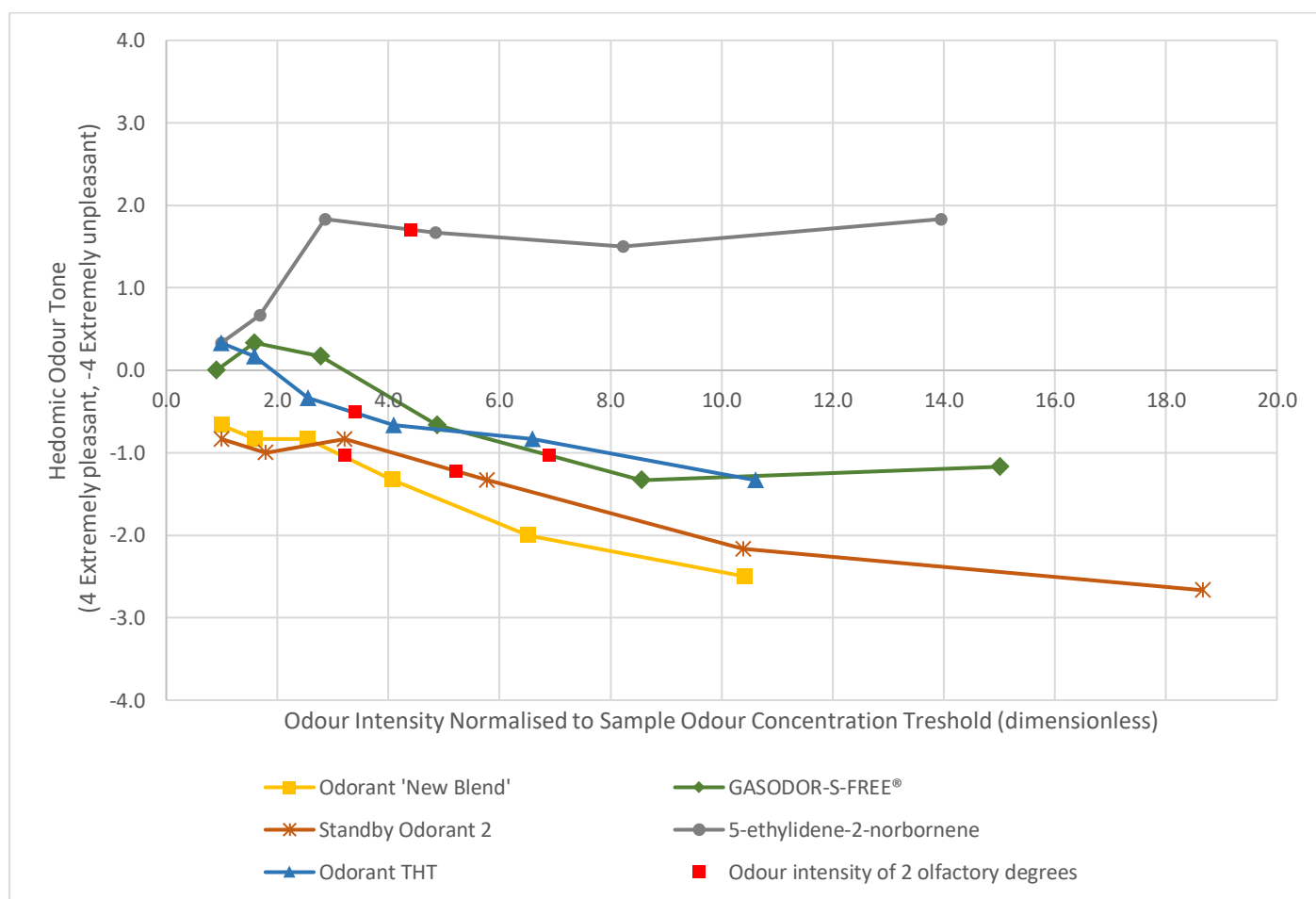
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196 *Figure 2: Result of the average intensity perceived by the panellists at various dilution points of gas sample triplicates. The error bars show the*  
 197 *range of responses provided for all panellists for all 3 rounds. The dotted lines are the Weber-Fechner model approximation.*

## 198 Hedonic Tone Results

199 The hedonic tone results aimed at assessing the pleasantness of each odorant at different dilution levels are  
 200 presented in Figure 3. The results are the arithmetic mean of the hedonic ranking for each panellist at the proposed  
 201 dilution levels. The dilution levels are then normalised by dividing the gas sample threshold detection concentration  
 202 by the dilution level presented. For a dilution level equal to the initial gas concentration threshold the normalised

value is 1 (i.e. dilution of the gas sample to its detection level). The results show that both the Odorant New Blend and Standby Odorant 2, both currently in use in the UK gas distribution networks illicit unpleasant perceptions in the panellists, even when diluted to the point of being barely detectable (i.e. at threshold concentration). Odorant THT and GASODOR®S-FREE® are both perceived as unpleasant at concentrations that would be encountered in the gas network or in the event of a leak (i.e. at concentrations allowing a minimum intensity of 2 olfactory degrees, eliciting a medium odour, to be detected), but do show pleasant perceptions when they are highly diluted and close to the detection threshold. 5-ethylidene-2-norbornene is the only odorant which is perceived as pleasant over the entire range of dilutions tested.



211

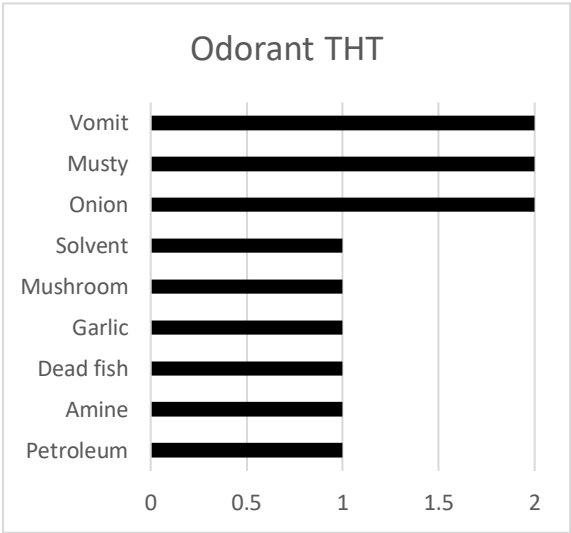
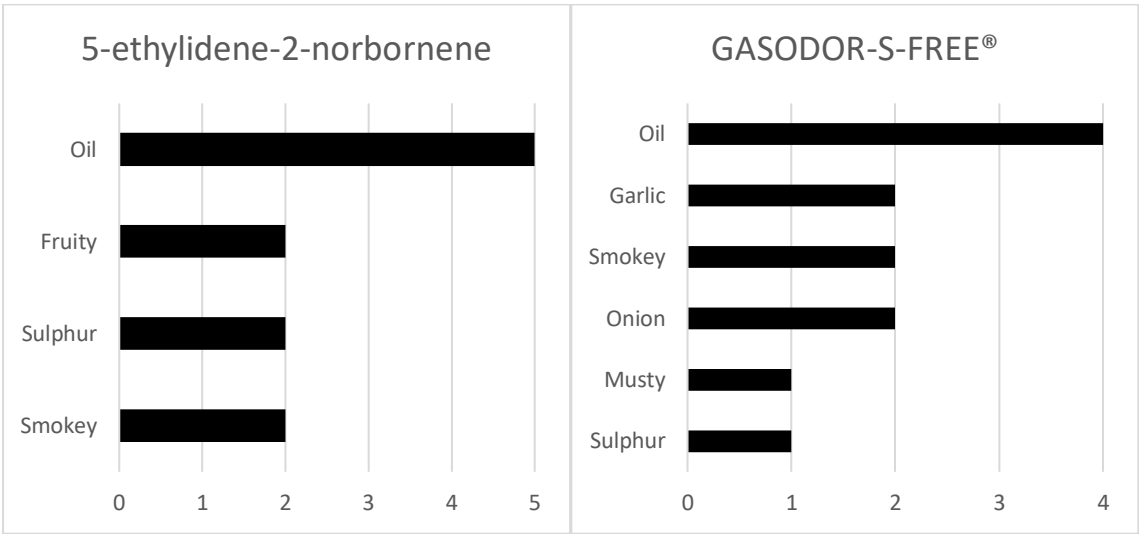
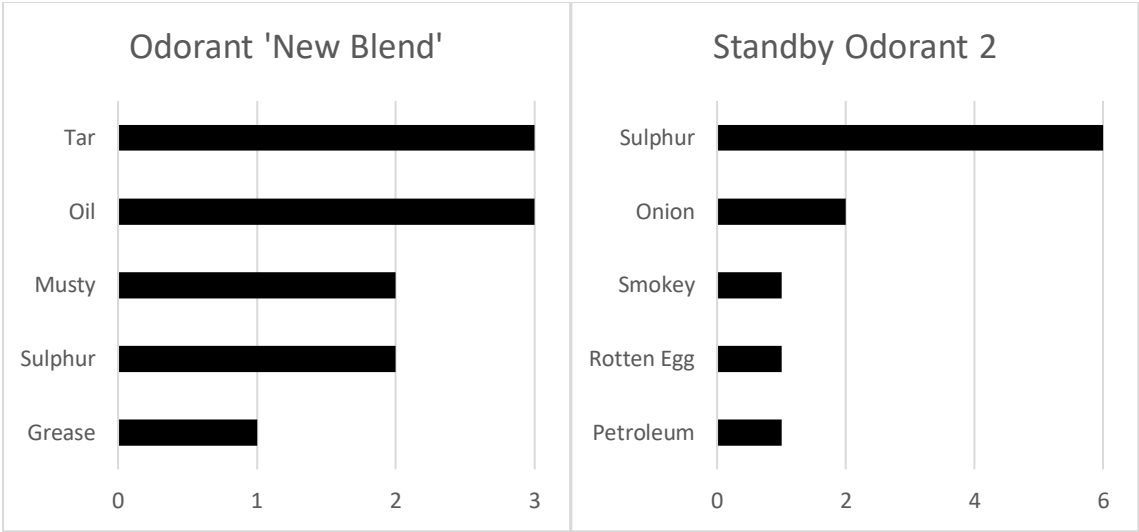
Figure 3: Averaged hedonic tone results for different concentration levels of samples of odourised gas. The dilution levels are normalised by dividing the dilution level by the detection threshold concentration of the sample gas. The red squares indicate the hedonic tone found at the minimum legal threshold of 2 olfactory degrees, eliciting a medium odour. The results indicate that Odorant 'New Blend' and Standby Odorant 2 both illicit a negative (unpleasant) perception in the panel. Samples odourised with Odorant THT and GASODOR®S-FREE® produce slightly positive (pleasant) perceptions in the panel when strongly diluted (i.e. close to the detection threshold), and are perceived as unpleasant at 2 olfactory degrees and as concentrations increases. The only odorant to illicit a pleasant reaction in the panellists is 5-ethylidene-2-norbornene.

## Odour Character Results

The results from the odour characterisation test are reported in Figure 4. The 6 panellists were provided a list of descriptive terms to describe the odour character. The results show that Standby Odorant 2 is being perceived as having a sulphur character by all the panel members. Similarly, all but one panellist identify an 'oil' character in 5-

222 ethylidene-2-norbornene. Odorant THT leads to the most varied reaction in the panel, with no more than one third  
223 of the panellists selecting the same descriptive term. No more than seven terms are used to describe the odour  
224 character and no less than four. In Figure 5 it can be seen that oil and Sulphur are dominant characters in the  
225 odorants tested, with a total of 12 and 11 votes each. This is followed by 6 votes for an onion character.

226



230 Figure 4: The odour character of the undiluted gas samples evaluated by the panel based on a list of terms provided. The results show that  
231 odorant THT is perceived as having a wide range of odour characters, whilst 5-ethylidene-2-norbornene and Standby Odorant 2 both show  
232 strong oil and sulphur character respectively.

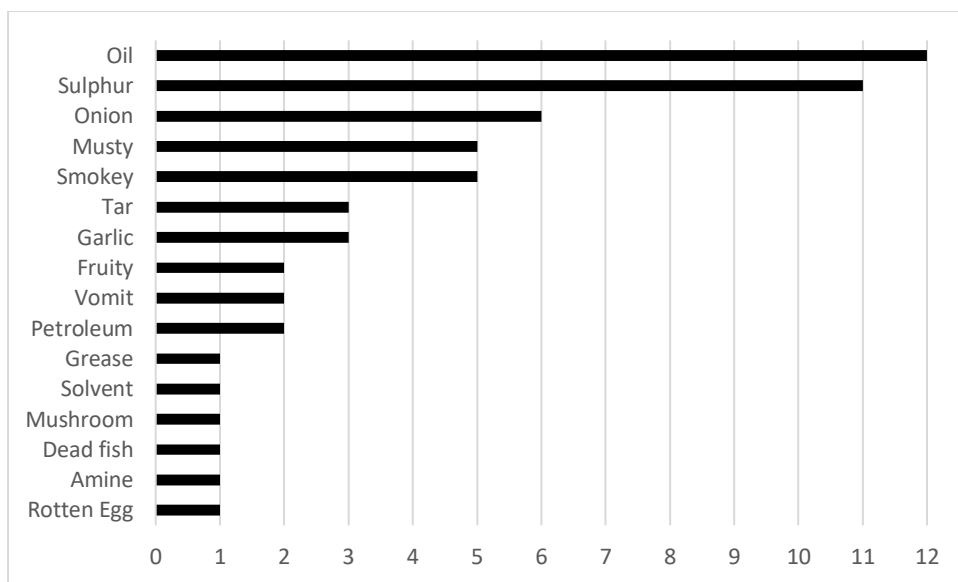


Figure 5: Total counts for each of the descriptive terms reported in the odour character study.

## Discussion

Odour detection threshold: Odorant 'New Blend' is the odorant that imparts the greatest odour concentration to the gas sample at concentrations found in UK gas distribution network. Odorant THT, which is widely used in the European mainland, on the other hand imparts the lowest odour unit concentration to the gas sample. This is an interesting result that provides an upper bound of 148,361  $\text{OU}_\text{E}/\text{m}^3$  and a lower bound of 20,789  $\text{OU}_\text{E}/\text{m}^3$  for odorants which are both in use in the industry and provide adequate alert levels to meet safety standards. The 5-ethylidene-2-norbornene odorant which has been investigated as it is sulphur-free and as such would be compatible with fuel-cells (Imamura et al., 2005) imparts an odour unit concentration 54,644  $\text{OU}_\text{E}/\text{m}^3$  of hydrogen that falls between the lower bound and the upper bound.

The odour threshold concentration analysis however needs to be complemented with odour intensity analysis to determine the suitability of an odorant as its perceived intensity does not decrease linearly with increasing dilution level (Fechner, 1860). As such, the starting odour concentration of a gas sample is not necessarily reflective of its intensity at various dilution levels. This is highlighted by the fact that the GASODOR®S-FREE® odorant, despite imparting 29,393  $\text{OU}_\text{E}/\text{m}^3$  to the gas sample, can only be diluted around 40,000 times before it's perceived intensity drops below the 'medium intensity' level of 2° on the Sales scale. This contrasts with the gas sample odorised using THT which can be diluted up to 70,000 times before its perceived intensity is lower than 2° on the Sales scale. This shows that despite the higher initial concentration of 29,393  $\text{OU}_\text{E}/\text{m}^3$  for GASODOR®S-FREE® compared to that of 20,789  $\text{OU}_\text{E}/\text{m}^3$  for THT odorant, THT odorant's perceived intensity is more resilient to dilution which is beneficial in the case of a leak.

254 The odour intensity analysis revealed that Weber-Fechner's law can be used to estimate the perceived intensity of  
255 an odourised gas sample at different dilution levels. It is noted that in the region of low intensity between a 'feeble  
256 odour' and a 'very feeble odour' the goodness of fit of Weber-Fechner's law drops. This can be explained by  
257 logarithmic relationship between the perceived intensity and the odour concentration which implies that a very  
258 large difference in odour concentration, in the vicinity of the detection threshold concentration, will result in a small  
259 difference in perceived intensity (typically less than the intensity scale resolution used). This makes the  
260 measurements of odour intensity at concentration within 0.6 to 1 time the detection threshold concentration less  
261 reliable. This highlights the importance of diluting odorants to a level which allows a perceived intensity of 2° or  
262 more at further dilution levels to ensure the odorant performs its function as an efficient warning system. The  
263 measurements made in this study show that at a dilution of about 125, leading to a gas volume in air of 20% of the  
264 lower flammability limit of hydrogen (i.e. 0.8 % gas in air) current standards offer perceived odour intensities in  
265 excess of 2° on the Sales scale and hence would be applicable to hydrogen. Indeed, even at the lowest dilution level  
266 considered here of 979, for the GASODOR®S-FREE® odourised gas, the perceived odour intensity was of 3.3° on the  
267 Sales scale.

268 The odour hedonic testing revealed that 5-ethylidene-2-norbornene was perceived as pleasant by the panel  
269 members, which should rule it out as a standalone alternative to odorants currently in use. It is a regulatory  
270 requirement that the odour character should be unpleasant (BS EN ISO 13734:2013). This is a key finding, which  
271 differs from a previous study which concluded to an hedonic tone ranging from pleasant to unpleasant (Small &  
272 Hellman, 1974). This indicates that testing designed around the end-use of hydrogen gas network odourising is  
273 necessary to evaluate odorants effectively.

274 The odour characterisation study revealed that the currently used odorants in the UK gas distribution network,  
275 odorant 'New Blend', share's a sulphur character with fuel cell compatible (chemically sulphur free) GASODOR®S-  
276 FREE® and 5-ethylidene-2-norbornene odorants. This would ensure some continuity in the odour character  
277 attributed to a "gas leak" in the UK and could contribute to safety and public acceptance of hydrogen for domestic  
278 uses. The odorant THT, used on the European mainland, on the other hand has shown to be a distinctive blend of up  
279 to 9 different odour characters. This is in accordance with regulation requiring a 'distinctive' character to be  
280 imparted to the gas so that it cannot be confused with other odours. However, this might lead to a very different



odour than the one currently in use being adopted. This would require careful consideration, and work to be done to inform citizens of the change in gas odour.

Previous work has highlighted the discrepancy between the olfactory abilities of young (18 to 25 years) and old (70 to 85) people to detect odourised natural gas (Stevens, Cain, & Weinstein, 1987). This indicates that it is important to have standards that account for this and use of safety regulations that impose odourising practices that are conservative to ensure even the members of the public with olfactory deficits can reasonably detect gas leaks. These limitations in experimental studies due to the discrepancy between panellist olfactory acuity and that of the public should be understood in the historical context of olfactory testing rather than regarded as a limitation.

Indeed (Harreveld, Heeres, & Harssema, 1999) highlight that around 4 decades ago most olfactory testing aimed to realise testing using panels representative of the wider population. This attempt proved unsuccessful due to the practical limitations involved. Current practices involve the use of a normalised system with normalised units such as the European Odour Unit. This enables laboratories to adjust their methodologies in order to achieve benchmarked and reproducible results. This in turn enabled regulations to rely on consistent tests and standards. This is why this study was performed in an accredited laboratory with certified panellists, and why the study focuses on dilution levels which are much higher than what would be expected in the case of a gas leak.

Following on from this olfactory assessment, further work to determine the physical and chemical stability of the odorant during transport, storage, and end use within a hydrogen network has been undertaken by NPL. These aspects have been highlighted as challenges (Najjar, 2013). This work addresses the following areas, what effect the odorant would have on the physical properties of the pipe, fittings, and boiler flame, as well as the impact of the odorants on fuel cells and an economic analysis. Together with the work presented here, this additional work will provide a holistic assessment of odorants for use in hydrogen networks.

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## Author Contributions

AM and MW designed and supervised the work undertaken and contributed to the manuscript. AM from National Physical Laboratory has designed the experimental programme and along with SB reported the results of the experimental programme commissioned to Air Spectrum Environmental Limited and conducted by PB and AW. JMC has performed complementary analysis of the work, a literature review on the topic of odorant use in 100% hydrogen gas networks and written the manuscript. SH has contributed to writing the manuscript.

## Competing Interest Statement

We certify that any and all of our affiliations with, or financial involvement with, any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript are disclosed in the funding acknowledgments section of this manuscript.

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